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## Double pion production in $NN$ and $\bar{N}N$ collisions

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With an effective Lagrangian approach, we give a full analysis on the  $NN \rightarrow NN\pi\pi$  and  $\bar{N}N \rightarrow \bar{N}N\pi\pi$  reactions by exploring the roles of various resonances with mass up to 1.72 GeV. We find large contributions from  $\Delta$ ,  $N^*(1440)$ ,  $\Delta(1600)$  and  $\Delta(1620)$  resonances. Our calculations also indicate sizeable contributions from nucleon poles for the energies close to the threshold. A good description to the existing data of different isospin channels of  $NN \rightarrow NN\pi\pi$  and  $\bar{N}N \rightarrow \bar{N}N\pi\pi$  for beam energies up to 2.2 GeV is reached. Our results provide important implications to the ABC effect and guidelines to the future experimental projects at COSY, HADES and HIRFL-CSR. We point out that the PANDA at FAIR could be an essential place for studying the properties of baryon resonances and the data with baryon and anti-baryon in final states are worth analyzing.

*Keywords:* nucleon-nucleon collisions; antinucleon-nucleon collisions; meson production.

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### 1. Brief summary of current status

Our understanding on the low energy strong interaction physics is still unsatisfactory though quantum chromodynamics (QCD) has been established as the standard theory of strong interaction for many years. Because of its color confinement non-perturbative properties, we have difficulties to calculate the properties of mesons and baryons directly from QCD. Constituent quark models are developed to explain the mesonic and baryonic spectrum and they are successful in some aspects.

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But one of severe problems is that they predict more excited states around 2 GeV than what have been observed experimentally. As a result, a lot of efforts have been devoted to the meson production in pion-, photo-, and electro-induced reactions in order to reduce the uncertainties of extracted parameters of resonances, deepen our knowledge on the structure of the resonances and search for missing resonances.

In the past few years, the double pion production in nucleon-nucleon collisions tends to be a fascinating field for studying resonances properties and has been accurately measured at the facilities of CELSIUS<sup>1</sup>, COSY<sup>2</sup>, KEK<sup>3</sup>, and PNPI-Gatchina<sup>4</sup>. In the Table 1, we list all the data measured after the year of 2000. The CELSIUS<sup>1</sup> and COSY<sup>2</sup> Collaboration measured the differential cross sections of  $pp \rightarrow pp\pi^+\pi^-$  and  $pp \rightarrow pp\pi^0\pi^0$  channels for the beam energies from the threshold to 1.3 GeV. One of the promising findings was that the  $N^*(1440)$  contribution dominates at the close-to-threshold region, as expected by the Valencia model<sup>5</sup>. This provided us a good place to explore the properties of  $N^*(1440)$  whose theoretical interpretation is still under controversial. However the Valencia model, though compatible with the old bubble chamber and magnetic spectrometer data<sup>13</sup>, overestimated the new data at the close-to-threshold energies by several times. Another finding was that the CELSIUS data of  $\pi\pi$  invariant mass spectra for the beam energies above 1.0 GeV demonstrated a single peak at the low invariant mass while the model gave double hump structure which was inconsistent to the data. The model also predicted a preferential parallel emission of the two pion-meson, which was contrary to the CELSIUS data. The third interesting finding was that there was a level-off behavior around the beam energies of 1.0 GeV in the energy dependence of the  $pp \rightarrow pp\pi^0\pi^0$ , which was thought to be the result of interference between different contributions. KEK Collaboration made another progress and they measured the total cross section of  $pn \rightarrow pn\pi^+\pi^-$  and  $pn \rightarrow pp\pi^-\pi^0$  channels which were important for our understanding on the excitation of  $N^*(1440)$ .

Table 1. The data of nucleon-nucleon collisions measured after the year of 2000. Those with the data of differential cross sections are marked by bold characters for the beam energies.

Channel	Collaboration (Tp (MeV))
$pp \rightarrow pp\pi^+\pi^-$	CELSIUS( <b>650, 680, 750, 775, 895, 1100, 1360</b> ), Gatchina(717, 818, 861, 900, 980), COSY( <b>750, 800</b> ), KEK(698, 780, 814, 908, 995, 1083, 1172)
$pp \rightarrow pp\pi^0\pi^0$	CELSIUS(650, 725, 750, <b>775, 895, 1000, 1100, 1200, 1300, 1360</b> )
$pp \rightarrow nn\pi^+\pi^+$	CELSIUS(800, <b>1100</b> )
$pp \rightarrow pn\pi^+\pi^0$	CELSIUS(725, 750, 775, 1100)
$pn \rightarrow pn\pi^+\pi^-$	KEK(698, 780, 814, 908, 995, 1083, 1172)
$pn \rightarrow pp\pi^-\pi^0$	KEK(698, 780, 814, 908, 995, 1083, 1172)

On the other side, though the role of  $N^*(1440)$  in nucleon-nucleon collisions was firmly established, its contribution in  $\bar{N}N \rightarrow \bar{N}N\pi\pi$  reactions has never been considered. JETSET<sup>6</sup> measured the  $\bar{p}p \rightarrow \bar{p}p\pi^+\pi^-$  channel in order to search for

narrow resonances decaying to  $\bar{p}p$  but they only included the double- $\Delta$  diagram in their Monte-Carlo simulation. Moreover, it has never been explored whether it was possible to extract the properties of other resonances from antinucleon-nucleon collisions.

The one-pion exchange (OPE) models<sup>7</sup> of more than 45 years ago only considered the double- $\Delta$  diagram and the Valencia model of more than 10 years ago made a further step by including also the  $N^*(1440)$  resonance and the  $\sigma$ - and  $\rho$ -meson exchange. With the new accurate data, it is very necessary to perform a more comprehensive analysis including more resonances and matching all the data of (anti)nucleon-nucleon collisions.

## 2. Description of our model

Our full model is demonstrated in Ref. 8, so herein we only give a brief description to the main features. The effective Lagrangians for the resonances in our model are based on a Lorentz covariant orbital-spin (L-S) scheme<sup>9,10</sup>. In view of the overall system invariant mass about 2.8 GeV for  $T_p = 2.2$  GeV, we have checked contributions from all the well-established  $N^*$  and  $\Delta^*$  resonances below 1.72 GeV. The coupling constants appearing in relevant resonances are determined by the empirical partial decay width of the resonances taken from Particle Data Group (PDG) book<sup>11</sup>. Our calculated results show that the  $N^*(1440)$ ,  $\Delta(1232)$ ,  $\Delta^*(1600)$ , and  $\Delta^*(1620)$  resonances play the relatively significant role in the considered energies and other resonances give negligible contributions<sup>8</sup>.

In our model, the adjustable parameters are the cut-off values in form factors at vertices and resonances. We include five types of form factors: those at the meson-(anti)nucleon-(anti)nucleon vertices, those at the meson- $N^*(\Delta^*)$ -(anti)nucleon vertices, the Blatt-Weisskopf barrier factors at the  $N^*(1440)$ - $\Delta$ - $\pi$  vertex<sup>12</sup>, the form factor at the  $\sigma$ - $\pi$ - $\pi$  vertex, and the form factor of resonances and nucleon poles. The  $pp \rightarrow nn\pi^+\pi^+$  channel is very useful to pin down these cut-off values in form factors of the relevant  $\Delta$  and  $\Delta^*$  resonances because it has negligible  $N^*$  contribution, and then we could easily determine the cut-off values of  $N^*$  resonances in other channels.

## 3. Results and discussion

If the double- $\Delta$  mechanism is dominant at high energies as in the OPE model and Valencia model, the total cross section of  $pp \rightarrow pp\pi^0\pi^0$  should be a factor of about four larger than that of  $pp \rightarrow nn\pi^+\pi^+$  according to isospin coefficients. However, the new exclusive measurements indicate an approximately equal value of these two channels, which is consistent to the old bubble-chamber data<sup>13</sup>. After calculating all the possible contributions, our model got two important conclusions:

- (i) Our model reduces the relative branching ratio of  $N^*(1440) \rightarrow \Delta\pi$  and assumes a smaller cutoff parameter for the  $\pi N\Delta$  coupling so the relative contribution

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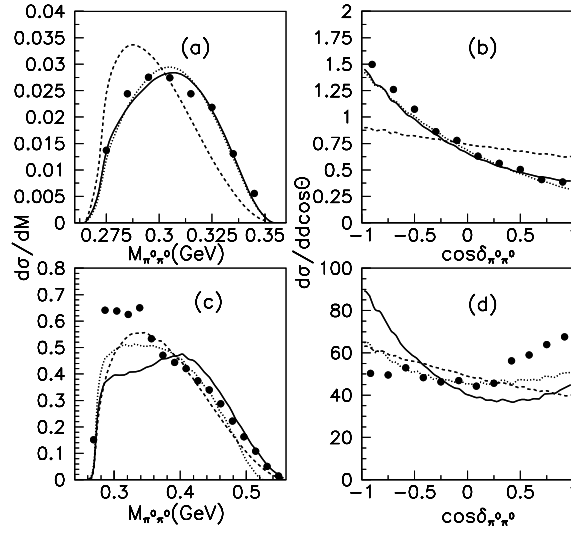


Fig. 1. The invariant mass spectra and angular distributions of the opening angle for  $\pi^0\pi^0$  system<sup>8</sup> in the overall center-of-mass system for  $pp \rightarrow pp\pi^0\pi^0$  at the beam energies of 795 MeV (a, b) and 1300 MeV (c, d). The dashed and solid curves correspond to the phase space and full model distributions, respectively. In (a, b), the dotted curves correspond to  $N^*(1440) \rightarrow N\sigma$  contributions. In (c, d), the dotted curves correspond to double- $\Delta$  contributions.

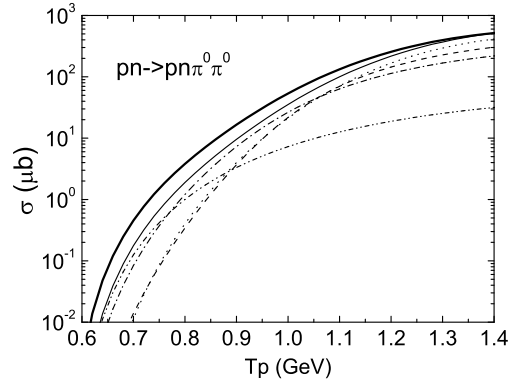


Fig. 2. Total cross sections of  $pn \rightarrow pn\pi^0\pi^0$  reaction. The dotted, dash-dotted, dashed, dash-dot-dotted, solid and bold solid curves correspond to contribution from double- $\Delta$ ,  $N^*(1440) \rightarrow N\sigma$ ,  $N^*(1440) \rightarrow \Delta\pi$ , nucleon poles, full model results without and with FSI, respectively.

- from the  $N^*(1440) \rightarrow N\sigma$  term increases significantly.
- (ii) our model introduces significant contributions from  $\Delta \rightarrow N\pi \rightarrow N\pi\pi$  at energies near threshold and from  $\Delta^*(1600)$  and  $\Delta^*(1620)$  at energies above 1.5 GeV. This is more obvious in the  $pp \rightarrow nn\pi^+\pi^+$  channel because the isospin coefficients of these terms are much bigger than those in other channels.

As a result, our description of the total cross sections of all isospin channels is considerably improved and our results agree well with the new data of  $NN$  collisions in the close-to-threshold region. However, we find that it is difficult to interpret the  $\pi\pi$  invariant mass spectra for the beam energies above 1.0 GeV and the level-off behavior around 1.0 GeV in the total cross section of the  $pp \rightarrow pp\pi^0\pi^0$  channel. In Fig. 1, we give the invariant mass spectra and angular distribution of the opening angle for  $\pi^0\pi^0$  system in the overall center-of-mass system in the  $pp \rightarrow pp\pi^0\pi^0$  channel at the beam energies of 795 MeV and 1300 MeV. At 795 MeV, which is close to the threshold, the  $N^*(1440)$  is dominant and the given spectra is consistent to the data. At 1300 MeV the model fails to describe the data because the  $N^*(1440) \rightarrow \Delta\pi$ , which is significant at high energies, gives a double hump structure in the  $\pi^0\pi^0$  invariant mass spectrum. But if the  $N^*(1440)$  contribution is negligible which is caused by some kind of destructively interference in this energy region, then the double- $\Delta$  diagram, which is dominant by  $\pi$ -meson exchange in our model, describe the data well<sup>1</sup>. The situation is similar in the  $pp \rightarrow pp\pi^+\pi^-$  channel.

Our model provide essential hints to the ABC effect in  $pn \rightarrow d\pi^0\pi^0$  reaction<sup>14</sup>. In Fig 2 we show the total cross section of  $pn \rightarrow pn\pi^0\pi^0$  channel. It can be seen that the  $N^*(1440) \rightarrow N\sigma$  and  $N^*(1440) \rightarrow \Delta\pi$  are significant in all the considered energies. At the close-to-threshold region, the nucleon poles are very important. So it is suggested that the  $N^*(1440)$  resonance and nucleon poles should be carefully considered before we reach the right conclusion<sup>15</sup>.

The agreement between our model and the data of  $\bar{N}N$  collisions is good<sup>16</sup>. It should be addressed that the  $N^*(1440)$  and other resonances should be included in the Monte-Carlo simulation of the experimental analysis in order to get the correct total cross sections from limited measured phase space, which is overlooked by the previous measurements. We find that the  $\bar{p}n \rightarrow p\bar{n}\pi^-\pi^-$  reaction is useful to determine the model parameters because like the  $pp \rightarrow nn\pi^+\pi^+$  reaction, the  $N^*$  contribution is small. We also point out that other channels in antinucleon-nucleon collisions could serve as a good place for studying baryon resonances.

A lot of precise measurements in nucleon-nucleon collisions are being carried out by CELSIUS and COSY collaborations in order to study  $N^*$  and  $\Delta^*$  resonances. Besides, the HADES collaboration has measured some channels of  $NN$  collisions at the beam energies of 1.25 GeV<sup>17</sup> and their results are expected to come soon, so this will constitute a good test of our model. Recently, a cooler storage ring HIRFL-CSR, which can produce the proton beam with similar beam energy range of COSY, has already been successfully installed at Lanzhou. With the scheduled  $4\pi$  hadronic detector for complete measurement of diverse differential cross sections, it will have

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a special advantage for studying excited nucleon states through nucleon-nucleon collisions. We also suggest that the double pion production in antinucleon-nucleon collisions should be measured at PANDA (anti-Proton ANnihilation at DArmstadt) at the GSI Facility of Antiproton and Ion Research (FAIR), which could provide the antiproton beam of kinetic energy ranging from 1 to 15 GeV with the luminosity of about  $10^{31} \text{cm}^{-2} \text{s}^{-1}$ . We address that PANDA could play an important role in the hadronic physics with a  $4\pi$  solid angle detector with good particle identification for charged particles and photons. The planned new experiments are anticipated to offer more tools and information to help us understanding the low energy physics better.

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